

## The site conditions of the Guo Shou Jing Telescope

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**Abstract** The weather at Xinglong Observing Station, where the Guo Shou Jing Telescope (GSJT) is located, is strongly affected by the monsoon climate in north-east China. The LAMOST survey strategy is constrained by these weather patterns. In this paper, we present a statistics on observing hours from 2004 to 2007, and the sky brightness, seeing, and sky transparency from 1995 to 2011 at the site. We investigate effects of the site conditions on the survey plan. Operable hours each month shows strong correlation with season: on average there are 8 operable hours per night available in December, but only 1-2 hours in July and August. The seeing and the sky transparency also vary with seasons. Although the seeing is worse in windy winters, and the atmospheric extinction is worse in the spring and summer, the site is adequate for the proposed scientific program of LAMOST survey. With a Monte Carlo simulation using historical data on the site condition, we find that the available observation hours constrain the survey footprint from 22<sup>h</sup> to 16<sup>h</sup> in right ascension; the sky brightness allows LAMOST to obtain the limit magnitude of  $V = 19.5$  mag with  $S/N = 10$ .

## 1 INTRODUCTION

The Guo Shou Jing Telescope (also named as Large Sky Area Multi-Object Fiber Spectroscopic Telescope, or LAMOST) is a quasi-meridian reflecting Schmidt telescope with a 4-meter aperture, a 5-degree field of view, and 4000 fibers installed on the focal plane (Cui et al. (2010); see also the overview

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by Zhao et al. 2012). It will be used as a spectroscopic survey telescope for Galactic (Deng et al. 2012) and cosmological science.

LAMOST is located at Xinglong Observing Station (here after XOS) of National Astronomical Observatories, Chinese Academy of Sciences (NAOC). It is located  $\sim 170$  km northeast of Beijing with longitude of  $7^{\text{h}}50^{\text{m}}18^{\text{s}}$  east and latitude of  $40^{\circ}23'36''$  north. The elevation of the site is about  $\sim 900\text{m}$ .

The site weather is extremely seasonal and is dominated by a continental monsoon in the summer. In this paper we show how the site climate, weather, sky brightness, and seeing influence the design of the LAMOST survey. These constraints are extremely important not only to the field selection for the halo on dark night (Yang et al. 2012), on bright night (Zhang et al. 2012), and for the disk (Chen et al. 2012), but also for the science goals of the LAMOST survey (Deng et al. 2012).

There have been a few previous papers on the XOS conditions. The early work on monitoring the site conditions with a Schmidt telescope was done by Zhou, Chen & Jiang (2000). Liu et al. (2003) used the the North pole monitoring data collected from 1995 to 2001 by the 60/90cm Schmidt telescope on the same site to investigate the sky brightness, the seeing and the atmosphere extinction. They found that the mean sky brightness in  $V$  band reaches  $21.0 \text{ mag arcsec}^{-2}$  and the mean seeing measured from the imaging FWHM varies with seasons; specifically, the seeing is better in summers but worse in winters. The camera used for seeing measurements on the Schmidt telescope undersamples the point spread function, so that the seeing measurements are not reliable when measured seeings are better than  $\sim 2''$ . The site seeing was also measured using a DIMM (Liu et al. 2010).

Previous studies either used old data or included only a short time baseline. These measurements do not reflect the current weather and long term variation of the site conditions. Since LAMOST will last at least 5 years, understanding the long term variation of the site conditions is very important in designing and planning LAMOST surveys. In this paper we will revisit XOS quality as an astronomical observing site using the largest and latest site parameter data set available, covering almost 16 years since 1995.

In Section 2, we describe how the data is collected. In Section 3 the weather patterns, the sky brightness, the seeing, and the atmospheric extinction are analyzed. We then create a simplified but realistic simulation of the survey with the priors of the site conditions so that the probability of the sky coverage and the total number of the spectra are estimated, and present that in Section 4. Finally, in section 5 we give general guidelines that will be used in the design of the survey.

## 2 DATA ACQUISITION

In this work we use two sets of data, both obtained from the BATC survey (Beijing-Arizona-Taipei-Connecticut multi-color photometry survey, Fan et al. 1996) using the Schmidt telescope at XOS.

The observation logs of BATC from 2004 to 2007 provide the duration of actual observing time from opening to closing the dome on each each night of operation. It is noted that the BATC is a 60/90 cm Schmidt telescope on an equatorial mount, therefore it can point to whatever part of the sky is clear, so that it is more time efficient than LAMOST. LAMOST is limited to point only within 2 hours on each side of the meridian, and is also restricted to  $-10^{\circ}$  to  $60^{\circ}$  in declination. (Higher declinations are possible, but at a significant cost to the field of view.) Therefore, the actual observation time available for LAMOST could be lower than BATC's statistics.

The other data set comes from Polaris area monitoring images collected by BATC from 1995 to 2011. The BATC survey took an image of the north celestial pole before normal observations on each night. Although it does not use the zenith, which is a better direction for monitoring the sky brightness, it is a great legacy to quantify XOS conditions. Liu et al. (2003) used the first 6 years of data in their work. In the current work, we extend it to 2011, 10 years more than was previously available.

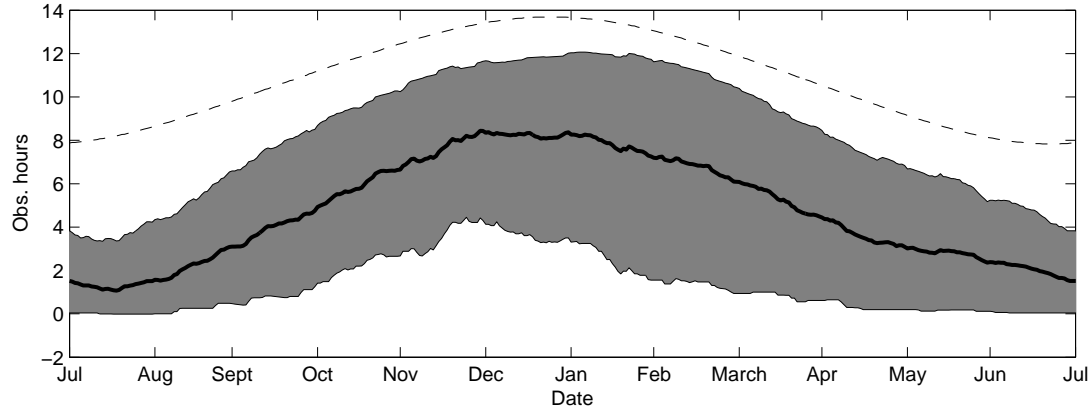
We follow the same procedure used by Liu et. al. (2003) to measure the seeing, night sky brightness and extinction from the Polaris dataset:

The sky brightness ADU was measured from the background of the images, then instrument magnitude zero points derived from photometric nights were interpolated to each observing night to convert the sky brightness ADU into the magnitude in  $V$  band. The photometric software package SExtractor (Bertin,1996) was used to measure the FWHM, magnitude and other parameters of stellar objects on

the image. The average FWHM of those stellar objects was taken as the seeing of that observation. The sky transparency, which is quantified by the extinction coefficient, was derived by comparing measured magnitudes of the selected stars with the known magnitude of the same objects from Guide Star Catalog (GSC, Lasker et al. 2008).

### 3 SITE PARAMETERS

#### 3.1 Weather patterns

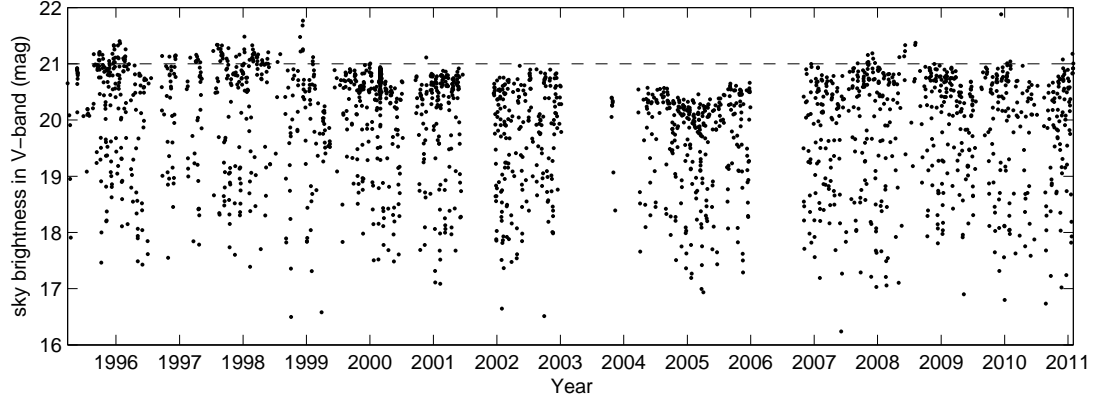


**Fig. 1** The statistics of the number of hours of BATC observations per night from 2004-01-01 to 2007-09-30. The thick solid line shows the actual mean observing hours, smoothed with a 2-month window, at each night from July 1 to Jun 30 the next year. The shaded area shows the minimum and maximum hours of observation each night smoothed with the same time window. As a reference, the dashed line shows the theoretical available time between evening and morning twilights.

Fig. 1 shows hours per night used for actual observations by BATC from 2004 to 2007. Although the recorded observed hours from BATC should not be identical to that for GSJT, it does reflect the general weather pattern at XOS. Fig. 1 shows that the actual observation hours per night is about 6 hours less than the theoretical value at all times of the year. In this period of time, 43% of observing time was lost to bad weather. The maximum observing time is in December and January, when about 8 hours on average are available each night, while in July and August the average observing time is less than 2 hours. This pattern is similar to Figure 1 in Zhang et al. (2009) paper. Because it is restricted to observe within  $\sim 2$  hours of the meridian, LAMOST hardly has any observation time in summer. Such a site dependent weather pattern means that LAMOST will have a better chance to observe right ascensions that are observable in winter; the Galactic anti-center and south Galactic cap. The north Galactic pole and the inner Galactic disk, on the other hand, are difficult to completely sample with LAMOST.

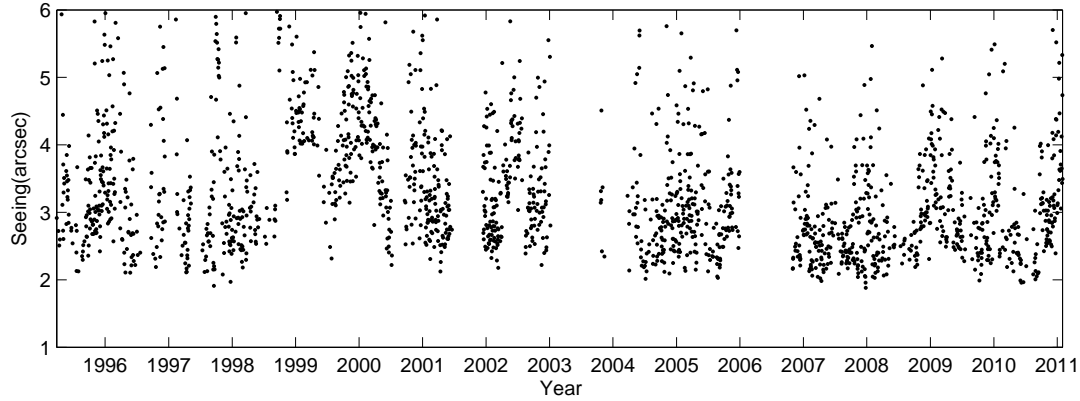
#### 3.2 Sky brightness

Fig. 2 shows the all sky brightness measurements from the BATC Polaris images as a function of time. There are some long term features in the data. First, there is a significant brightening between 2005 and 2006, which is due to the construction of the buildings for LAMOST. Lights from the construction site significantly affected the BATC telescope, which is only a few hundred meters away. After the construction was done in 2007, the monitoring data from BATC returned to the normal level for the site.

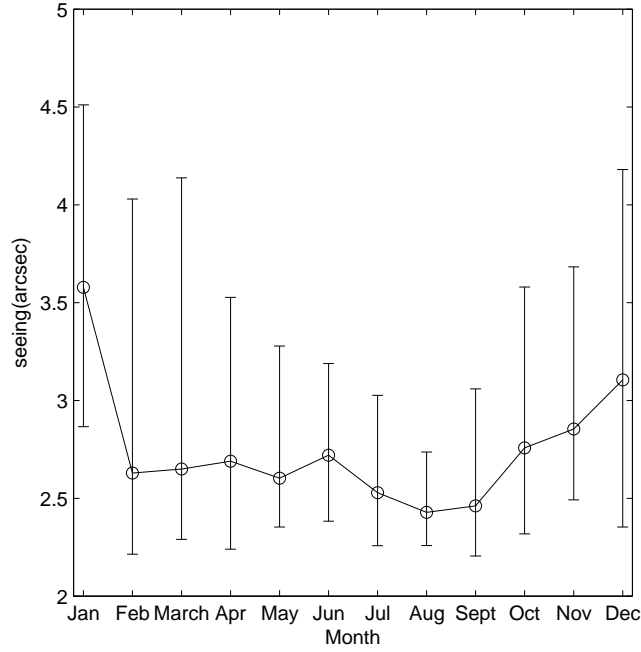


**Fig. 2** The sky brightness in  $V$  band obtained from BATC Polaris monitor data, as a function of time from 1995 to 2011. The dashed line is  $21 \text{ mag arcsec}^{-2}$ .

Second, there seems to be an annual (probably seasonal) variation in the sky brightness. The periodical pattern is much clearer from 2007 to 2011. It seems that around the end of a year, i.e., in the winter, the sky is darker, sometimes fainter than  $21 \text{ mag arcsec}^{-2}$ , while in the middle of a year, i.e., in the summer, is brighter by as much as 0.5 mag. It is not well understood what causes the seasonal pattern in the sky brightness. Several factors could have contributed to the pattern, including dust storms in the spring, more construction at local areas in summer or local agricultural activities. All of these factors reduce the transparency of the atmosphere, which can result in more scattered light from nearby cities.



**Fig. 3** The seeing measured from the FWHM of the Polaris-region images obtained by BATC from 1995 to 2011 is shown in this figure.

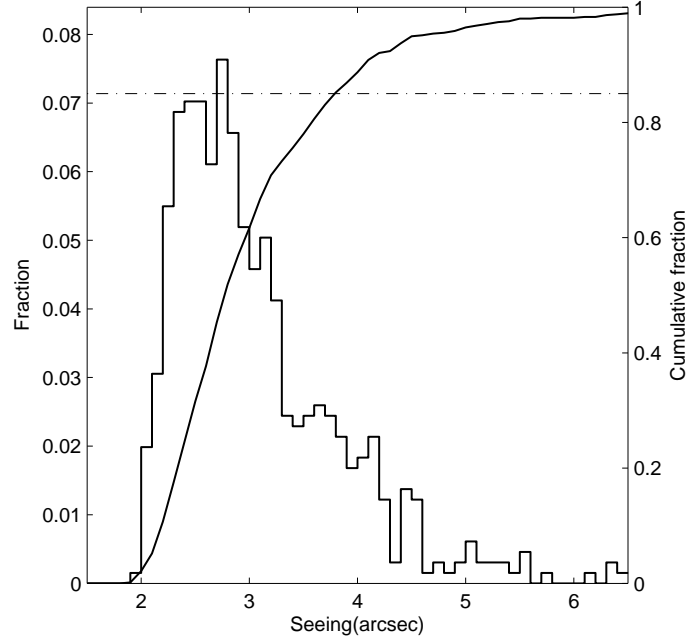


**Fig. 4** The median seeing and its  $1-\sigma$  range using the data after 2007 in Fig. 3 in each month are shown here.

### 3.3 Seeing

There are no specific instruments dedicated to monitoring site quality, especially natural seeing, at XOS. The most reliable data set that can be used for seeing assessment is BATC data archive. However, note that the Schmidt telescope has a classical dome, with attached office and living facility, so the measurements are likely dominated by dome seeing. The site natural seeing is most likely much better than these measurements. The long term record of seeing of XOS derived from BATC is shown in Fig. 3. The seeing spans a huge range and is probably seasonal, as is clearly seen in the figure. In the winters of 1999 and 2000, it was rather bad in general, and sometimes was worse than 4 arcsec. It became slightly better in 2006. There are several possible explanations for the improvement. One possibility is that a new  $4k \times 4k$  CCD was installed at the main focus the Schmidt telescope in that year. The new camera improved the imaging resolution from 1.7 arcsec/pixel to 1.36 arcsec/pixel. This consequently slightly improves the measurement of the seeing from the FWHM of the stars. An alternative reason is that the weather since 2007 at XOS has been better. Anyhow, in Fig. 3 it is quite clear that the data after 2007 have a slightly lower median seeing than the earlier data, and also look more stable than before 2007. Therefore we only use the data after 2007 for subsequent analysis.

Fig. 4 shows the average seeing for each month using the data after 2007. The best seeing occurs in August and September, while the worst is in December and January. Meanwhile the dispersion of the seeing (the error bar shown in the figure) also follows the same trend. This pattern is similar to Fig 7 of Liu et al. (2003), and also Figure 5 of Zhang et al. (2009). Experience from other telescopes at the same site show that it's true that the seeing is worse in the winter and better in the summer. This is related to the climate. In winter the strong and frequent wind significantly enhances the turbulence in the atmosphere and hence the seeing is worse and more unstable. In contrast, in summers there is very weak or no wind and this makes the seeing smaller and more stable.



**Fig. 5** The distribution and cumulative distribution of the seeing after 2007, using data from Fig. 3. The solid lines show the distribution for all data. The dashed-dot horizontal line shows the position of 85.3%. It indicates that the 85.3% of the observations are in the seeing lower than 3.8 arcsec for the data.

Fig. 5 gives the statistics of the seeing after 2007. The peak of the histogram of the seeing is around 2.5 arcsec. Based on the cumulative distribution of the seeing data, 85% of the seeing measurements are better than 3.8 arcsec. Due to under-sampling, BATC images are not perfect for accurate seeing measurements. Even with the slightly improved pixel scale of 1.36 arcsec, the images do not yield good measurements of the FWHM below 2 pixels ( $\sim 2.7$  arcsec). Additionally, it is dome seeing dominant and not the natural seeing at the site. For these reasons, we will use the results only as a reference for the long-term variations in seeing condition. Nevertheless, although the seeing is not perfect comparing with other famous sites, it is adequate for the proposed science program with LAMOST spectroscopic survey.

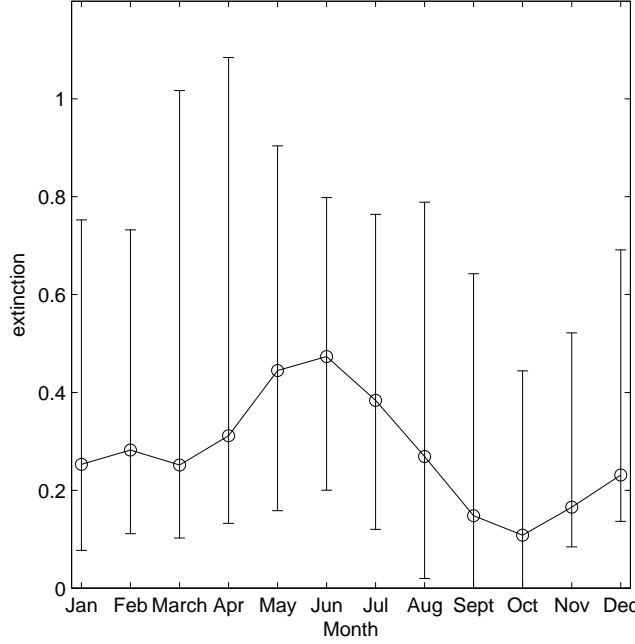
### 3.4 Extinction

The sky transparency at XOS shows significant seasonal variations, as shown in Fig. 6. The best value occurs in October, the worst value appears in May and June, when the local area suffers the sand storms and/or climate factors such as humidity and dust.

## 4 A SIMULATION FOR THE LAMOST SURVEY WITH SITE CONSTRAINTS

We run a Monte Carlo simulation to simulate the sky coverage of the LAMOST survey based on the site conditions. The simulation helps to clarify how the site conditions affect the survey and consequently what science goals are the most feasible for LAMOST.

In the simulation, we assume that LAMOST can only observe 864 predefined non-overlapping 5-degree-diameter fields of view (hereafter denoted plates) covering all space between  $\delta = -10^\circ$  and



**Fig. 6** The circles show the median atmospheric extinction coefficient for each month. The error bars show the range of  $1-\sigma$ . Only the data after 2007 are used for this plot.

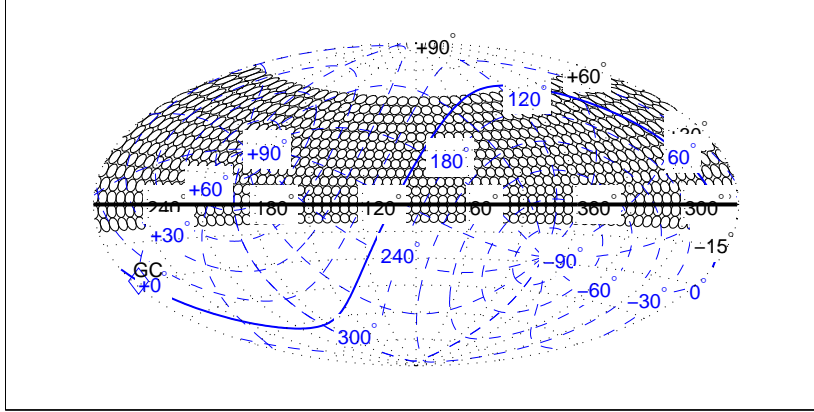
$\delta = 60^\circ$  (Fig. 7). This is an oversimplified assumption since in practice LAMOST scans the sky with many overlapped plates. However, this assumption makes the simulation quite simple and sufficient for investigating impacts of the site conditions on survey planning. No fiber assignment is included in the simulation. We also do not give any presumption of the favorite sky regions, e.g. the emphasizing of the anti-center direction as we did in Deng et al. (this volume), but just evenly cover all available sky regions for LAMOST.

We also assume that on dark/gray nights LAMOST observes the faint objects with 1.5 hour exposures ( $3 \times 30$  minutes), while at bright nights it only observes the bright objects with 0.5 hour exposure ( $3 \times 10$  minutes). The overhead for each plate is 0.5 hours, including telescope moving, active optics operation, fiber positioning etc. In addition, we add 2 more hours for each night for the telescope preparation and configuration, including focusing the mirrors on a bright star twice per night.

We adopt a very simple strategy for the simulated survey. On dark/gray nights, when LAMOST start to observe, it arbitrarily selects the one with the minimum number of observations from all available plates within 2 hours on each side of the meridian. On bright nights, the plates with zero observations will be the highest priority for observation. Additionally, the probability of plate selection follows the star counts in the area of sky covered by that plate; therefore plates near the Galactic mid-plane will be observed more than those in high latitudes.

We run the simulation for a five-year survey (2011–2015) and run it 50 times to smooth out the random fluctuations. The mean number of the plates observed in five years, at each location, is shown in Fig. 8. The bright night survey can reach to more than 5 observations per plate along the Galactic mid-plane. Since the Galactic plane, in particular the anti-center direction, is right in the most weather favorable sky region for LAMOST, it seems that LAMOST is suitable for an anticenter Galactic plane survey. Since the dark/gray night survey does not use any prior knowledge of the star distribution, it simply follows the actual number of observing hours available, considering the weather, seasonal





**Fig. 7** The footprint map in equatorial airtiff projection of the Monte Carlo simulation. The circles show the possible plate that LAMOST can observe in the simulation. The blue grid shows the Galactic coordinates. Note that some plates are blocked by the coordinate labels when draw the plot, they do actually exist behind the numbers.

variation in the number of hours per night, and moon phase. In 5 years, the dark/gray night survey can cover the sky between  $\alpha = 22^{\text{h}}$  and  $16^{\text{h}}$  at least three times. The rest of the region is the summer sky, which can be essentially covered only once. The actual observation hours in the summer restrict the sky coverage of LAMOST.

## 5 CONCLUSION

From a compilation of site condition data in the last 16 years, we find that the strongest constraint for the LAMOST survey is from the actual observation hours, which is significantly lower than the available hours due to weather constraints. This results in very few or even zero observation hours in summer. Considering the special quasi-meridian design, the observable sky is constrained to the autumn, winter and spring, so that LAMOST performs best in the regions of the Galactic anti-center and the South Galactic cap. Consequently, the survey plan has to be very carefully designed under this limitation.

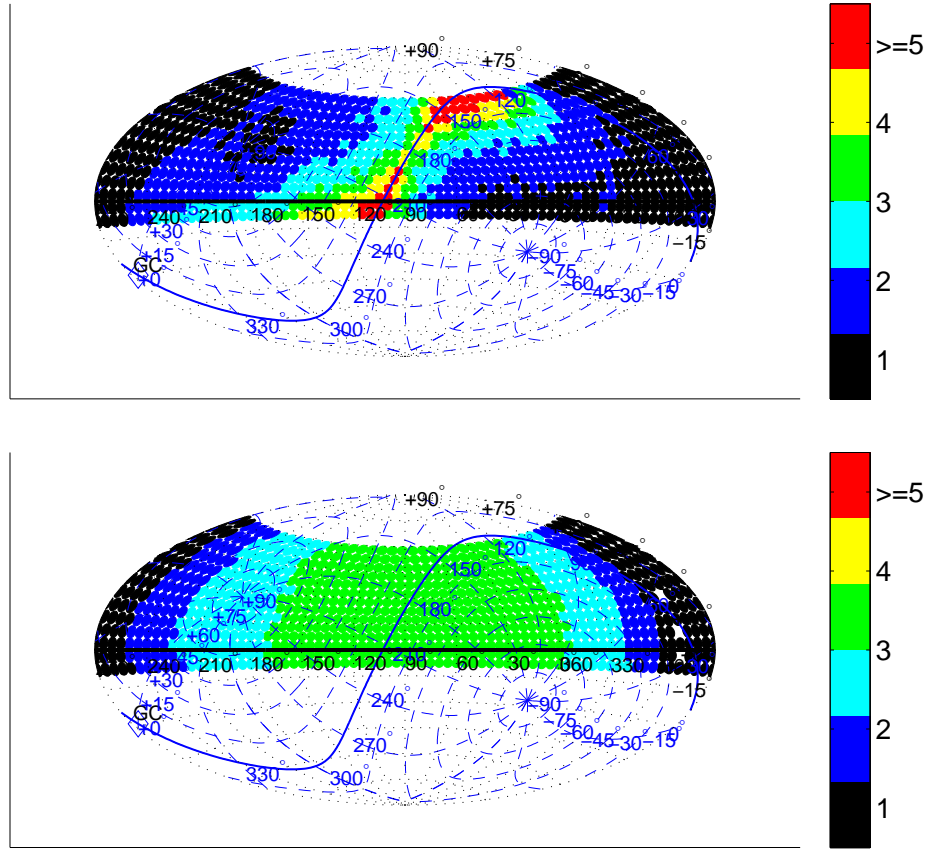
The sky brightness reaches roughly  $V = 21 \text{ mag arcsec}^{-2}$  on the best nights at Xinglong. Therefore the limiting  $V$  magnitude for spectroscopy should be around 19.5 mag with  $S/N = 10$  for point sources. This is the upper limit of the capability of LAMOST. Because the seeing at LAMOST site becomes worse during the months that the actual observation hours are long, LAMOST will suffer from flux lost due to the larger PSF, which will reduce the total throughput of the fibers to some extent.

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**Fig. 8** *Top panel:* The number density equatorial map of the observed plates at bright nights in five-year simulated survey. *Bottom panel:* The number density equatorial map of the observed plates at dark/gray nights.

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